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Validation of the SNOWPACK model in five different snow zones in Finland

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The performance of a snow pack structure model SNOWPACK was studied in five locations around Finland during two winters. Reasonable agreement between modelled and observed snow depth and snow pack structure evolution was found in all other locations except in coastal Santala. Agreement grew when going towards the north; better agreements were obtained during the early winter than during the melting period. Several test runs with changed input data were done for Hyytiälä. Water equivalent, temperature, grain form and grain size were the most sensitive of the model output quantities to changes in the input data. The use of measured precipitation instead of snow depth for driving the mass balance or the use of different radiation schemes had relatively large effects on the model output. Model sensitivity was high when many phase changes were involved such as during the melting phase in spring or in temperate climate zones.

Introduction

Snow cover is an important environmental factor in boreal and arctic nature. Globally it has significant effects on Earth's climatic system through its high albedo and large areal extent. The role of snow in smaller scale, for example in a single forest, is also of importance. Snow acts as a water storage, and it is possible that most of the precipitation (excluding sublimated part) fallen during the winter is freed during the melting period, including nutrition consisting of the various chemicals scavenged by the falling snow flakes from the atmosphere (Pomeroy and Brun 2001).

Snow on the ground can be defined as mixture of ice crystals, moist air and liquid water. It is a very porous material, and because of this an efficient insulator. Under the snow cover, air humidity and temperature change relatively little and are relatively high through the winter. Solar radiation is also dampened efficiently in the snow. Snow pack affects ecology, but it also can be controlled by the vegetation. For example snow density in Finnish fell plateau has an effect on the temperature regime in and under the snow cover, which in turn affects the vegetation type; on the other hand vegetation has an effect on the snow density (Eurola *et al*. 1980).

Properties of snow discussed above are not only due to the amount of snow, but also snow pack structure. Snow pack structure means description of internal stratigraphy of snow cover. Description consists of information about the amount of the layers, layer thickness and layer qualities: for example temperature, density, hardness, grain size and grain form. In addition, also snow microstructure can be described; this means information not only on the grain size, but also on the bond size and amount of bonds per grain. Also information about fractions of ice, water and air can be defined as part of the microstructure.

Combined properties of single layers define properties of the whole snow cover. On the other hand, the snow microstructure in single layers define those snow properties we are usually interested in. Snow heat conductivity, which determines temperatures inside the snow pack as well as snow insulating capacity, is mostly due to the grain bonding and fractions of different water phases; snow viscosity, which has an effect on snow settling and stability, is based on grain size, form and bonding; snow carrying capacity, which determines the animals' ability to move on the snow cover, is due to the grain bonding. Winter (not taking melting period into account) snow pack properties and effects on the environment cannot be satisfyingly studied without taking snow pack structure into account, and also if possible snow microstructure .

In Finland, the snow amount — depth and water equivalent — is measured and mapped regularly. Measuring snow pack structure is a time-demanding task, and in many cases it is not possible to cover large areas or perform measurements with a good temporal resolution. Snow pack structure modelling is a suitable tool when one is interested in snow properties where snow structure has an effect.

A Swiss SNOWPACK model was chosen as a model tool in this work. The most used snow pack structure models, in addition to SNOWPACK, are the French Crocus (Brun *et al.* 1992) and American SNTHERM (Jordan 1991). SNOWPACK is in operational use in Swiss avalanche warning. It has also been used in USA, Greenland, Japan and in many other European countries. SNOWPACK is the youngest of the three, and because of this perhaps not so efficiently validated. It is a developing model with sophisticated snow microstructure in it. The aim of this study was to estimate the usability of the SNOWPACK model in varying conditions in Finland with different types of input data, keeping especially the model use in the forests in mind.

Earlier SNOWPACK model validation studies include studies by Lehning *et al.* (1998, 2001), Lundy *et al.* (2001) and Etchevers *et al.* (2005). The studies by Lundy *et al.* (2001) and Lehning *et al.* (2001) include detailed statistical validation of the model, but they mostly concentrate on visual intercomparison of the model output and observations, as well as quantitative evaluation of mass and energy balance (Etchevers *et al.* 2005). Normally studies have concentrated on a few locations with similar snow climatology. No study of the model sensitivity to the input data has been conducted.

For these reasons, the aim of this study was to validate the SNOWPACK model in five different snow zones with different winter climates in Finland. Objectives and hypotheses included were as follows:

- To study the agreement between observed and modelled snow depth and water equivalent — better agreement for snow depth and for accumulation period, as compared with water equivalent and melting period, being as hypotheses.
- To study the agreement between observed and modelled snow pack structure — better agreement in areas with stable snow and climatic conditions, as compared with those with varying ones, being as hypothesis. Also the agreement between different structural parameters (density, grain size, etc.) was studied.

Additional objective was to make a thorough sensitivity test of the SNOWPACK model in relation to input data and model parameterisation. The model user has often a problem with the input data. Data has poor time resolution, the quality of data is questionable or some of the input parameters have to be estimated. In this study, the most sensitive output parameters were looked for, as well as input data changes with largest effects. Aim of this was to find out whether a user can rely on the estimation of the snow pack structure for used input data.

It was assumed, that different model parameterisation (like albedo or new snow parameterisation) or use of different boundary conditions (like fixed snow surface temperature or precipitation information) all have effect the modelled snow pack structure. Amount of snow was thought to be less sensitive to input data changes.

SNOWPACK model

SNOWPACK is a one dimensional snow pack structure model, which has been developed in the Swiss Federal Institute for Snow and Avalanche Research (SLF) for avalanche warning purposes. SNOWPACK is a predictive model that uses Lagrangian finite elements to solve for heat and mass transfer, stresses, and strains within the snowpack. The model calculates snow cover evolution during the winter: for example stratification, density, crystal structure, water equivalent and runoff. The model is physically based: energy balance, mass balance, phase changes, water and water vapour movement and wind transportation are included, and most of the calculations are based on snow microstructure (crystal size and form, bond size, number of bonds per crystal). A complete description of the model can be found in Bartelt and Lehning (2002), Lehning *et al*. (2002a), Lehning *et al*. (2002b).

As input, the model needs air temperature (°C), air humidity (0–100), wind velocity (m s^{-1}), wind direction (°), shortwave and longwave radiation (W m^{-2}), and snow depth (cm) or precipitation (mm in water equivalent), as well as surface and ground temperatures (°C), if possible. Ideal time resolution for the input data is 30 minutes, but even a 6-hour resolution can be used.

Data

Snow data

Overall performance of the SNOWPACK model was studied during two winters (1999/2000 and 2000/2001) in four locations in Finland: Santala, Mekrijärvi, Oulanka and Kilpisjärvi (Table 1). During the winter 2000/2001 an intensive model verification campaign was also carried out in Hyytiälä, and other during melt period in 2002/2003. Hyytiälä (61°51´N, 24°17´E) is located in thin maritime snow zone, and the main biotypes in the area are coniferous, mainly pine, forests and fields.

The comparison between the model output and snow pit studies including traditional measurements of snow pack layering, layer depth, temperature, density, grain size and grain type was made. Several snow pits were dug both in open areas and in the forest at each location. In the model testing only representative open area snow pack structure in flat land is taken into account. Several snow depth and water equivalent observations were also made on study locations. Data of snow depth was also collected from the Finnish Meteorological Institute (FMI), and snow water equivalent from the Finnish Environment Institute. In this way, continuous time series of these quantities could be gathered; in other locations than Hyytiälä snow stratigraphy were studied only twice a winter.

The snow depth and water equivalent measurements are standard measurements, and they are of good quality. The snow depth is however measured only from one point near the FMI

Table 1. Measurement locations and their description. Snow zones are described in Sturm *et al.* (1995).

Location	Coordinates	Snow zone	Main vegetation types
Santala	59°50´N, 23°15´E	Ephemeral	Mixed forest, field
Hyytiälä	61°51´N, 24°17´E	Thin maritime	Pine forest, field
Mekrijärvi	62°46´N, 30°59´E	Maritime	Mixed forest, pine forest, field
Oulanka	66°22´N, 29°19´E	Tundra	Mixed forest, pine forest, bog
Kilpisjärvi	69°03´N, 20°48´E	Taiga	Birch forest, fell plateau

weather station, and it does not necessarily tell the average open area snow depth. The water equivalent measurements have a poor time resolution. Quality of the snow pack structure data is variable. Several different observers have been gathering the data and this must have had an effect to the data quality. The winters in question were also different from each other.

Meteorological data

For all of the locations synoptic data with either 3-hour (Mekrijärvi and Kilpisjärvi) or 6-hour (Santala, Hyytiälä and Oulanka) time resolution was used as the input for the SNOWPACK model (Table 2).

As the set of input parameters required by SNOWPACK is a little bit different, the meteorological data had to be handled before running the model. The incoming short wave radiation was estimated using the method described first by Iqbal (1983), with alterations made by Venäläinen (1994). Laevastu (1960) cloud correction scheme was also used with this method. Niemelä *et al*. (2001) validated the methods and concluded that they give very reliable results for Finnish conditions. This method is described in detail in Grönholm (2003).

The snow surface temperature was set to air temperature, which is rather a rough estimate, when in many cases especially in clear conditions the snow surface may be several degrees colder than the overlaying air (Koivusalo *et al*. 2001). The colder snow surfaces were also observed in this work. Naturally the snow surface temperature cannot exceed 0 °C. The influence of the assumption is small as long as Neumann boundary conditions (BCs) are used. Neumann BCs require, however, to estimate longwave radiation from the sky. The ground surface temperature was set to 0 °C. The ground temperatures measured during this work were relatively close to 0 °C.

Incoming long wave radiation was estimated by the model. In the test runs described later also incoming long wave radiation was parameterized using a method differing from the one used in SNOWPACK model. This method includes cloudiness, and it is described in Omstedt (1990).

The quality of the FMI data was good, but the poor time resolution could make them an insufficient input for the snow cover modeling. The weather stations are situated in flat, open areas, in most cases small forest openings allowing good comparison of simulated and measured snow pack structures. In Santala and Mekrijärvi the distances between the measurement sites and the weather stations were 10–20 km, in other locations the weather stations were situated close to the measurement sites.

In Hyytiälä also meteorological data from the SMEAR II Station (Station for Measuring Forest Ecosystem–Atmosphere Relations) have been used (Table 3). The station is located at the Hyytiälä forest station of the University of

Table 2. FMI data used for the simulations.

Parameter (unit or scale)	Measurement height
Air temperature (°C)	2 m
Relative humidity (%)	2 m
Wind velocity (m s^{-1})	2 m
Wind direction (°)	2 m
Cloudiness (1–8)	–
Snow depth (cm)	–
Precipitation (Water Equivalent, WE) (mm)	–

Table 3. SMEAR II data used for the simulations.

Parameter	Unit	Device	Measurement height
Air temperature	°C	Pt-100 sensors, ventilated and shielded	4 m
Relative humidity	%	Teflon pipes and gas analyzer URAS 4	4 m
Wind velocity	m s^{-1}	Vector cup anemometer	4 m
Wind direction	°	Vector vane	Above canopy
Shortwave radiation	W m^{-2}	Reeman pyranometer	Above canopy

Helsinki, in the community of Juupajoki (Vesala *et al*. 1998).

SMEAR II data were of good quality. All measurements in Hyytiälä are half an hour averages calculated from 1-minute data. Unphysical or disturbed data are rejected before calculations (Grönholm 2003). Relative humidity is calculated from temperature and air water content. FMI measurements of snow depth and precipitation are used together with the SMEAR II data in Hyytiälä.

Model validation

Snow cover evolution

The following quantities were studied from both the simulated and real snow cover evolutions at all locations: snow cover formation, melt and duration (days), date of maximum snow depth, maximum depth (cm) and water equivalent of the snow cover (mm).

Rather large differences were seen between the observations in different years (Tables 4 and 5), but the overall tendency of increasing duration, maximum depth and water equivalent when going towards the north is clear. During snowy winters the snow depth and water equivalent in Mekrijärvi with maritime snow cover may also exceed the ones in Oulanka in the taiga zone due to higher overall precipitation.

It is easily seen that SNOWPACK uses the measured snow depth during the accumulation periods: observed and simulated snow cover formation, maximum depth and timing of it follow each other closely. Melt is however in most of the cases prolonged, and this increases simulated snow cover duration to unrealistic values, on average by 7%.

Table 4. Observed and simulated snow cover evolution in different locations.

	1999/2000		2000/2001	
	Observed	Simulated	Observed	Simulated
Santala				
Formation	19 Dec.	19 Dec.	29 Dec.	28 Dec.
Melt	19 Mar.	31 Mar.	12 Mar.	19 Mar.
Max date	30 Dec.	31 Dec.	26 Jan.	25 Jan.
Duration (days)	92	104	75	83
Max depth (cm)	9	7	14	13
Max WE (mm)	20	15	30	23
Mekrijärvi				
Formation	5 Nov.	5 Nov.	14 Nov.	14 Nov.
Melt	26 Apr.	9 May	21 Apr.	22 Apr.
Max date	17 Mar.	20 Mar.	5 Mar.	4 Mar.
Duration (days)	173	186	159	160
Max depth (cm)	111	110	59	58
Max WE (mm)	260	340	130	157
Oulanka				
Formation	11 Nov.	10 Nov.	20 Nov.	23 Nov.
Melt	7 May	10 June	2 May	1 May
Max date	10 Mar.	10 Mar.	5 Apr.	4 Apr.
Duration (days)	179	214	165	161
Max depth (cm)	106	105	75	75
Max WE (mm)	256	325	180	190
Kilpisjärvi				
Formation	9 Oct.	9 Oct.	30 Oct.	31 Oct.
Melt	1 June	16 June	13 May	1 June
Max date	29 Mar.	30 Mar.	12 Apr.	12 Apr.
Duration (days)	236	251	196	214
Max depth (cm)	124	123	74	73
Max WE (mm)	309	380	245	205

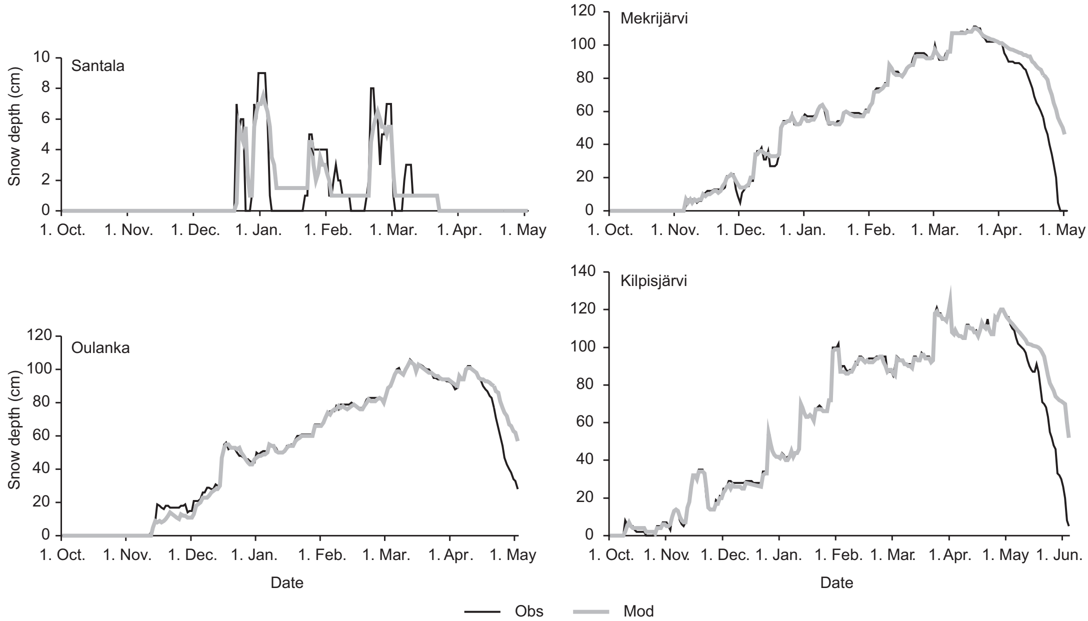

Fig. 1. The measured and simulated snow depths in winter 1999/2000. Snow depth data by FMI.

Observed maximum water equivalent may differ greatly from the real maximum water equivalent of the site because of the poor measurement resolution both in time and space. The differences between observations and simulations for this quantity may for these reasons be unrealistic. So further conclusions on water equivalent simulations are drawn only in Hyytiälä case. SNOWPACK tends to give too high maximum water equivalent values, which means too high densities when the snow depth is correct. The difference between observed and simulated water equivalents was on average 20%. The difference was greater during the snowy winters. In Santala the model gave exceptionally low values. No clear trend can be seen for the agreements when going towards the north.

Snow depth and water equivalent

Figure 1 presents the measured and simulated snow depths for each location except Hyytiälä for winter 1999/2000. The same is shown in Fig. 2 for Hyytiälä for winters 2000/2001 and 2002/2003. For the accumulation periods, the SNOWPACK model uses in the calculations the measured snow depth, but during blowing snow and settlement periods the snow depth is calculated by the model. Also during the melt period

Table 5. Observed and simulated snow cover evolution in Hyytiälä

	2000/2001		2002/2003	
	Observed	Simulated	Observed	Simulated
Formation	17 Dec.	24 Dec.	1 Nov.	24 Oct.
Melt	23 Apr.	26 Apr.	22 Apr.	23 Apr.
Max date	23 Mar.	22 Mar.	2 Feb.	8 Feb.
Duration (days)	127	123	172	181
Max depth (cm)	43	42	49	49
Max WE (mm)	95	117	100	125

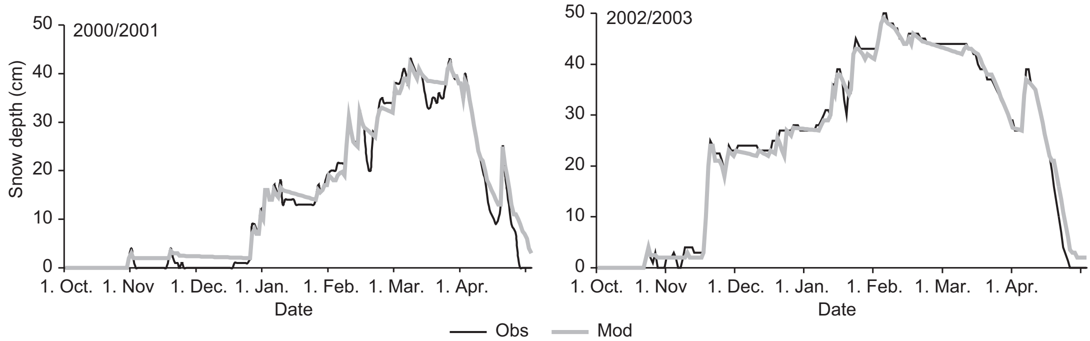

Fig. 2. The measured and simulated snow depths in winter in Hyytiälä. Snow depth data by FMI.

the snow depth is calculated independently from the measured one. When interpreting Figs. 1 and 2, most attention should be paid to these ablation periods and the agreement between simulations and reality.

The SNOWPACK has certain problems in representing the snow depth changes in Santala, but the overall variability of the snow depth typical for the ephemeral snow zone is seen. An interesting feature in the Hyytiälä simulation is the model's inability to melt all the snow away, when the snow cover forms and melts several times before the buildup of the winter snow cover. In Mekrijärvi, Oulanka and in Kilpisjärvi the winter snow depth is very well simulated, also the ablation periods with only a couple of exceptions. These exceptional periods are melt periods, not dry snow settling or blowing snow periods. In the spring, the modelled snow depth is typically overestimated for these sites, as the melting is too slow in the model. These features are also confirmed by comparison between observations and model outputs during winter 2000/2001.

Unfortunately data available on the water equivalent of snow were so sparse in time and space that no reliable validation of the water equivalent modelling could be done in other locations except Hyytiälä. In Fig. 3, both the simulated and measured water equivalents (WE) in Hyytiälä in winter 2000/2001, showing also some spatial variability, are presented. There is reasonable agreement between the measured and simulated values although in many cases water equivalents measured during the campaign or obtained from the Finnish Environment Institute were lower than the simulated ones. The distance

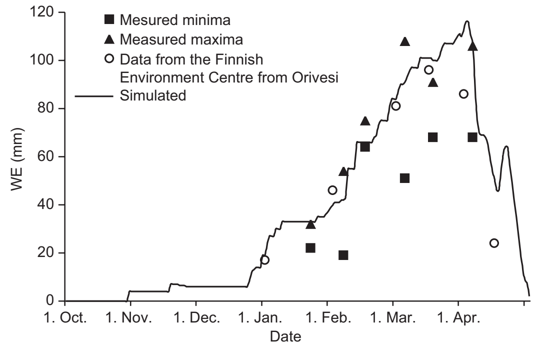

Fig. 3. Snow water equivalents (WE) in Hyytiälä in winter 2000/2001.

between the measurement and simulation locations makes the direct comparison difficult.

Visual comparison

The snowpack structure evolution for example in Hyytiälä in winter 2000/2001, can be shown as a SNOWPACK model graphic output (Fig. 4). Different shades of gray distinguish the different snow layers. Evolution of the stratigraphy is clearly seen, as well as temporal continuity of the layers. Shading used in this figure is based on the SNOWPACK output configuration.

The observed and modelled snowpack structure profiles for the measurement periods at different locations and in different winters were visually compared (Figs. 5–9). The main interest in the comparison was placed on the snow microstructure, and especially on the grain type of the snow. The grains were categorized into following types: precipitation particles, partly rounded grains, rounded grains, faceting grains,

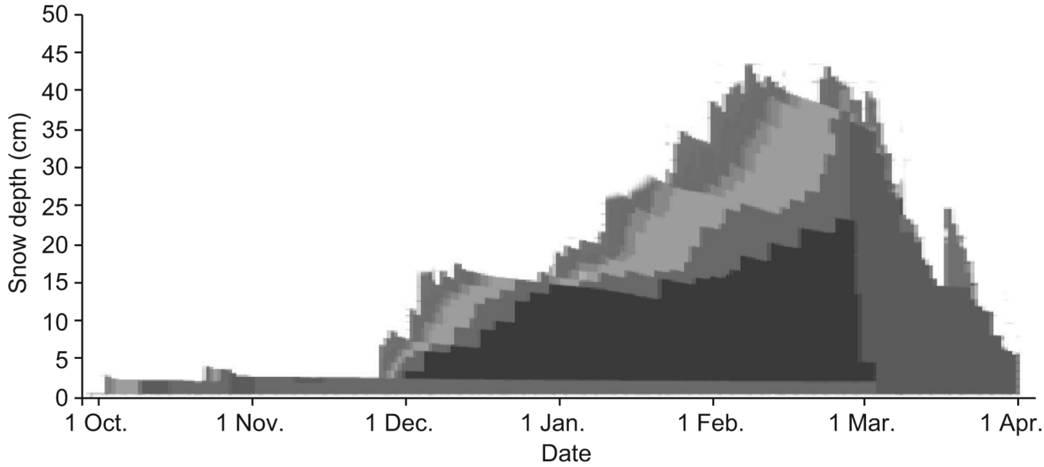

Fig. 4. Example of the SNOWPACK model snow cover structure evolution output, Hyytiälä winter 2000/2001. Different shades of gray distinguish the different snow layers. Please note that shading in this figure does not refer to the shadings in the following figures.

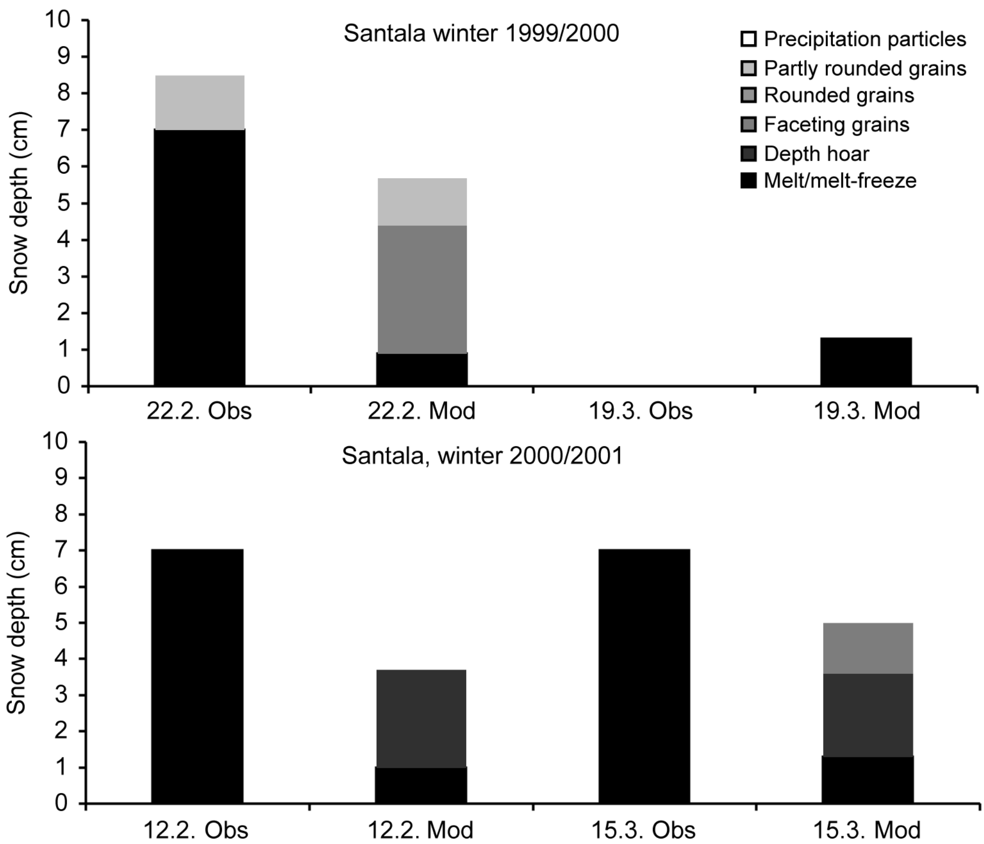

Fig. 5. The observed and modelled snow pack structure in Santala during early and late winters 1999/2000 and 2000/2001.

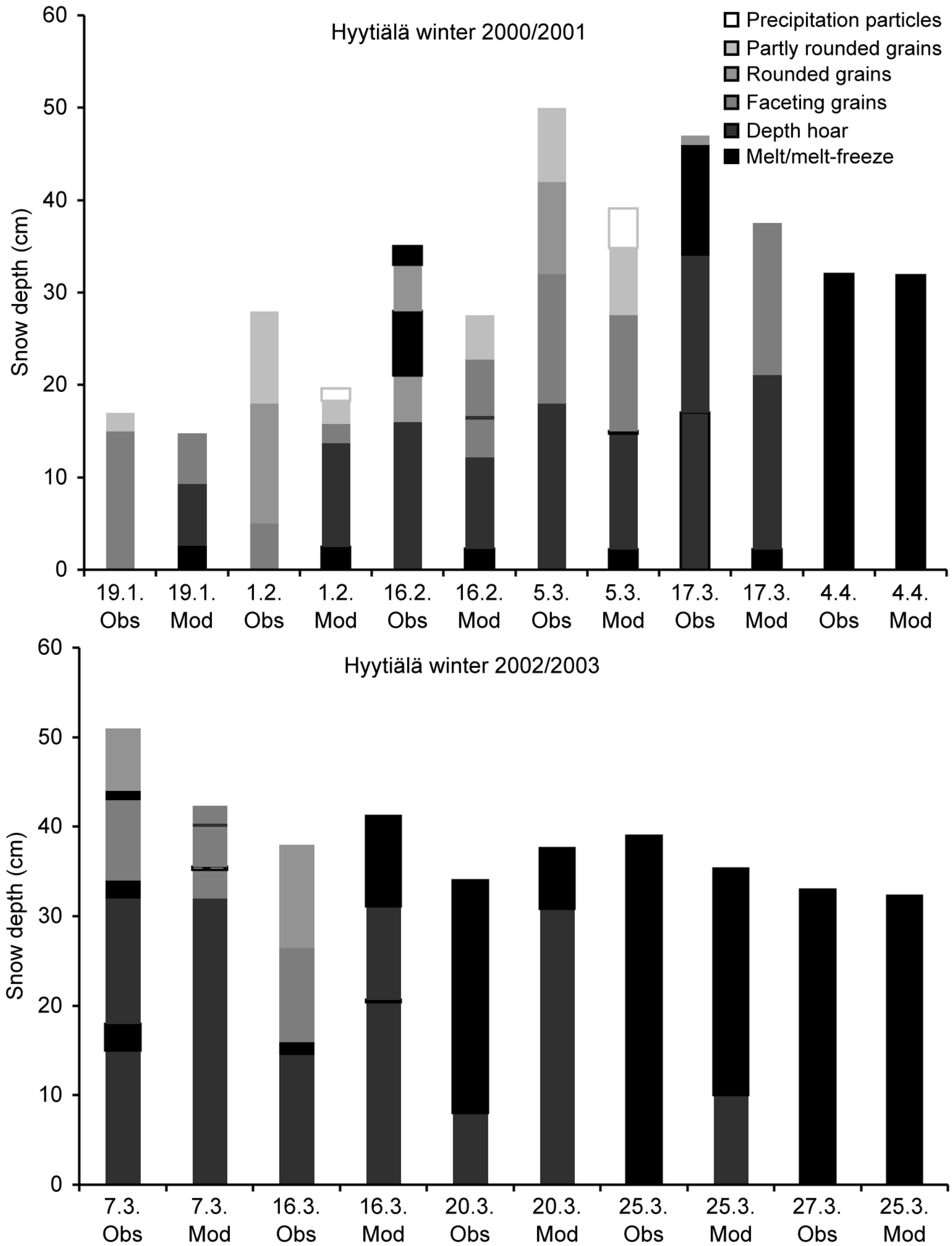

Fig. 6. The observed and model snow pack structure in Hyytiälä during early and late winter 2000/2001 and during melt period 2002/2003.

depth hoar (also surface hoar marked with the same shading), and melt/melt-freeze.

The modelled snow pack structure profiles are based on the SNOWPACK snow grain type outputs for a certain date and location; the observed ones are "average" open area profiles based on the snow pit observations for certain date and location.

It is important to notice the differences between observed snow depth and snowpack structure evolution at different locations and in different winters. Perhaps the most remark-

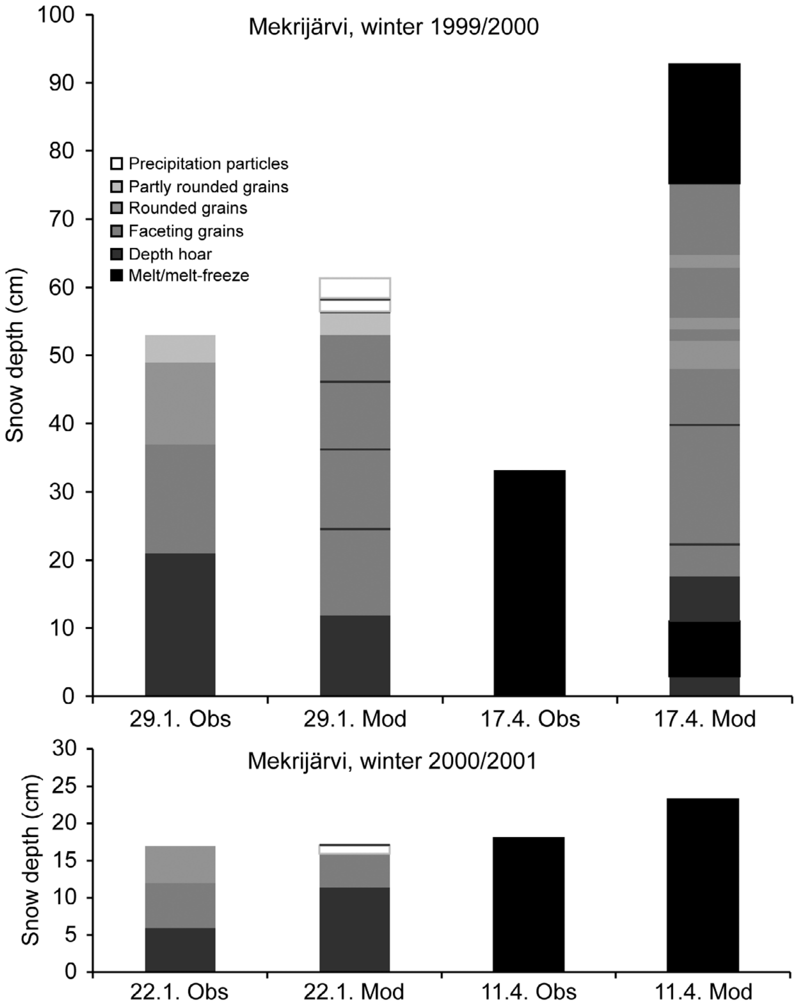

Fig. 7. The observed and modelled snow pack structure in Mekrijärvi during early and late winters 1999/2000 and 2000/2001.

able difference between winters 1999/2000 and 2000/2001 is the difference between the amounts of snow in most of the snow zones studied. In maritime, taiga and in the tundra zones the maximum snow depth in winter 2000/2001 was not much more than half of that in 1999/2000. Also the snow cover formed later and melted earlier in winter 2000/2001. In Hyytiälä, the difference between winters 2000/2001 and 2002/2003 was not that pronounced. There was more snow in Santala during 2000/2001 than during 1999/2000, but both in both winters, continuous snow cover formation and melt typical for ephemeral snow zone were recorded.

No marked differences in snowpack structure between the two winters were seen. In both winters, the simulated snowpack structure showed typical stratigraphies and grain type evolutions for the snow zone in question. In Santala the forming of either dry or wet snow cover and soon after this melt or melt-freeze of the snow was seen. When comparing with observations, most often too dry modeled snow covers were formed.

In Hyytiälä and in Mekrijärvi the maritime snow cover was formed; melt features were present in the snow cover, as well as quite a large fraction of rounded grains. In Hyytiälä the snow depth was lower, because this site is situated in a thin part of the snow zone. The snow cover simulated in Hyytiälä seems to be too cold to be realistic. It is also worth noting, that in Mekrijärvi on 17 Apr. 2000 the modelled snow cover had more than double depth as compared with

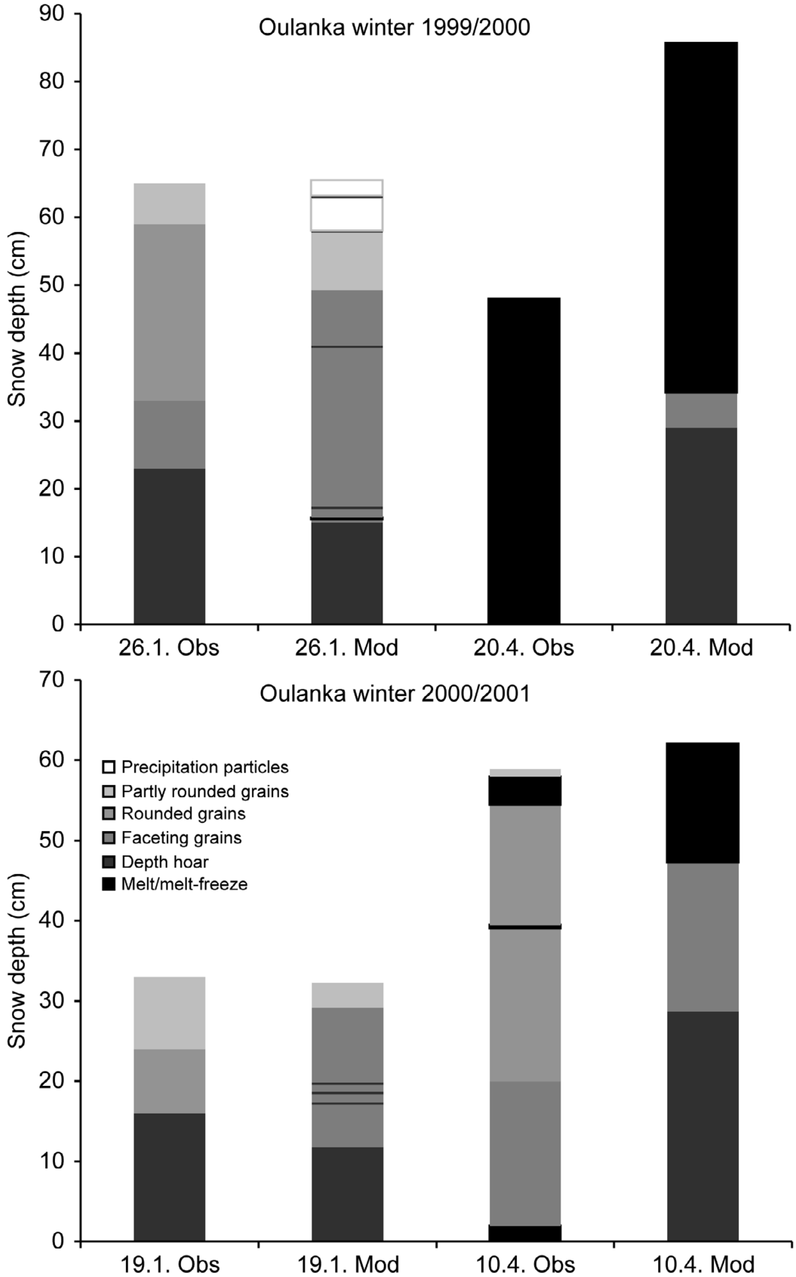

Fig. 8. The observed and modelled snow pack structure in Oulanka during early and late winters 1999/2000 and 2000/2001.

the observed one, as the measurements were carried out during the melt period. Also modelled snow pack structure was much too dry during the measurements.

The snowpack structures simulated in Oulanka and Kilpisjärvi were very similar, as expected, because the input data in Kilpisjärvi were from below the tree line. Both locations showed cold and dry snowpacks mainly consisting of new snow and faceted grains. During 1999/2000 also some melt features not typical for the Kilpisjärvi region were both observed and simulated. Too deep and dry snow cover was seen also on 20 Apr. 2000 in Oulanka simulations.

The simulated snow covers could be divided into two classes; wet and dry snow covers, which

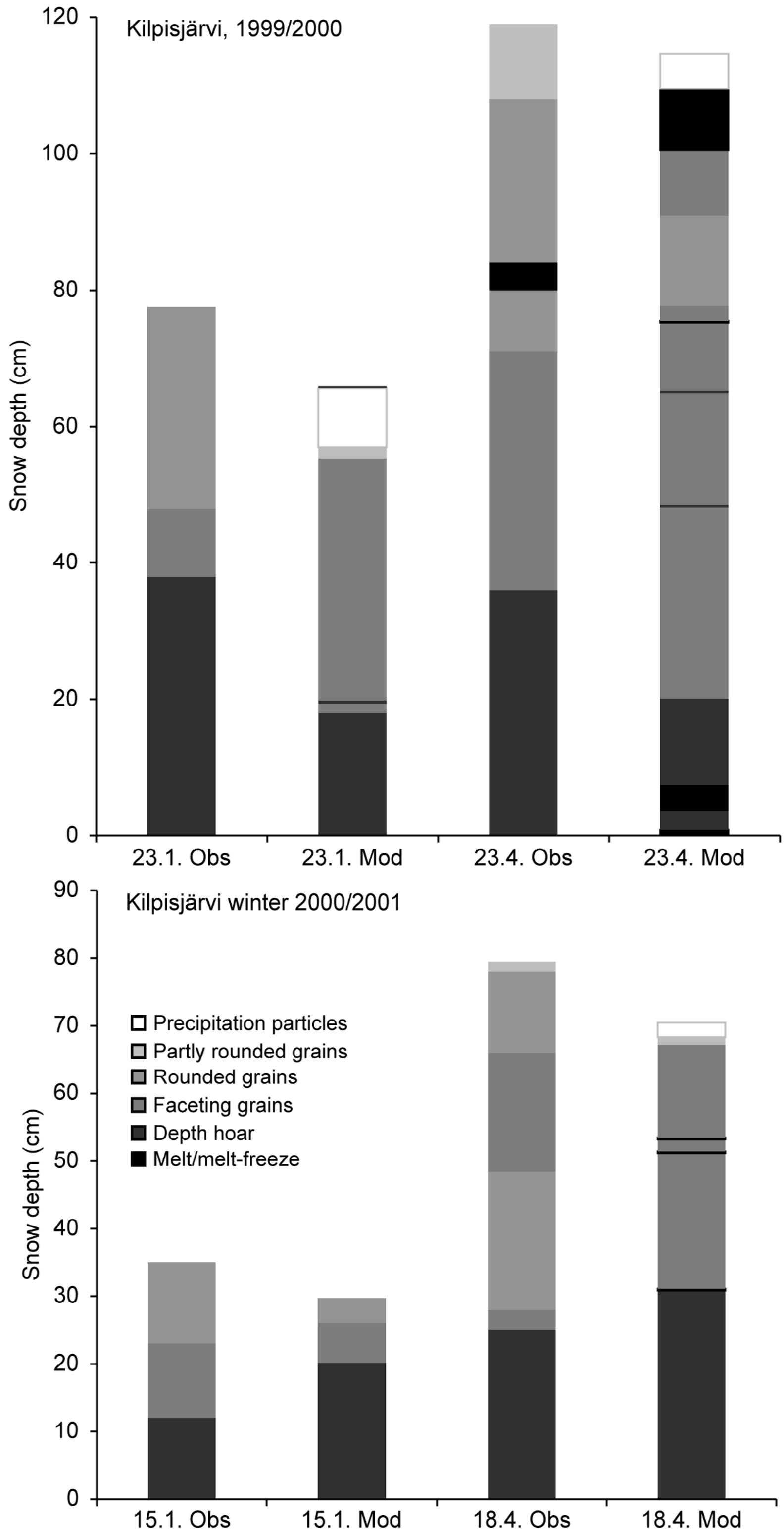

Fig. 9. The observed and modelled snow pack structure in Kilpisjärvi during early and late winters 1999/2000 and 2000/2001.

were separated by existence of the melt features in the snow cover during early and mid-winter. Locations in the ephemeral and maritime snow zones belong to the first, the ones in taiga and tundra zone to the latter. The taiga and tundra zone snowpacks could not be separated from each other on the basis of simulations, and not all the time the simulated maritime snow covers showed maritime features.

The overall agreement between measured and simulated snowpack structures varied from place to place. Only a few measurements were available to perform the comparison, so no far reaching conclusions can be made; the Hyytiälä situation was best because of the regular snow-pit measurements during 2000/2001 and melt period in 2003.

In this comparison, the differences in snow depth between simulation and measurements are not dealt with. The distance between snow pit measurement site and FMI snow depth measurement site may be several kilometers, and the local variability of the snow depth makes the comparison difficult, despite the fact that the snow-pit locations were chosen as representative for the location as possible.

Another problem in the comparison is the different description of the grain types by an observer and the model; also no two observers gave identical snow-pit observations. Consequently, no attention was paid to the slight differences in grain types. New or rounded snow, faceted snow and wet or refrozen snow were chosen as main categories for the grain types.

During the winter 2000/2001 some runs replacing the measured snow depth with FMI precipitation data were also made, and the observed snow pack structure profiles were compared with the modelled ones (Fig. 10). For some locations (Kilpisjärvi and Mekrijärvi) the model was not able to complete the calculations, most probably because of the large amounts of liquid precipitation during the melt season.

In Santala the model fails to reproduce the correct snow cover evolution with these boundary conditions. In Oulanka the beginning of the winter is reasonably well simulated, but later the amount of snow is largely underestimated (not shown). Also there are marked differences in the snowpack structure between these runs; the most significant feature was melt-freeze layer seen in the precipitation run output. This layer could also be found from the late-winter measurements, but not from the ones from early winter. In Hyytiälä the formation of the snow cover was quite realistic using the precipitation data, but there are errors in snow depth and timing of the snow melt. During most of the winter the snow pack stratigraphy was more realistically modeled using the precipitation data of Hyytiälä.

The solid precipitation error varies between 13% and 66% including the error caused by wind, wetting and evaporation. The error due to an unsuitable position is linked to the wind error. (Koivusalo *et al.* 2001) The precipitation data were also corrected using a method described by Solantie and Junila (1995) for Tretjakov type precipitation gauges. This method takes into account the effect of the wind and fastening of snow to the gauge. The simulated snow depths were still underestimated, when using this corrected precipitation data in the calculations.

The differentiation between the solid and liquid precipitation in the SNOWPACK model should not cause errors in the estimation of the amount of the snowfall. When the air temperature is below +1.1 °C, the precipitation is assumed to be solid. According to the study by Koivusalo *et al.* (2001), 25% of the precipitation is solid in Finland when the air temperature is +1.3 °C, 50% in +0.9 °C, 75% in 0 °C, and 90% in –1.2 °C.

In the model, the irreducible water content (the volumetric fraction of liquid water, after which the water begins to drain) is called residual water content. It is possible that rather a small value for residual water content, 0.05, has something to do with the failing of the model in some cases. In more recent model versions the value of 0.08 is being used. In a study by Koivusalo *et al.* (2001), the value was most often observed to be between 0.16 and 0.05 in Finland. On the other hand, in Kuusisto (1973), the value was observed to be between 0.02 and 0.05 in Finland.

Agreement scores

Not only visual comparisons between the simulated and observed snow pack stratigraphies

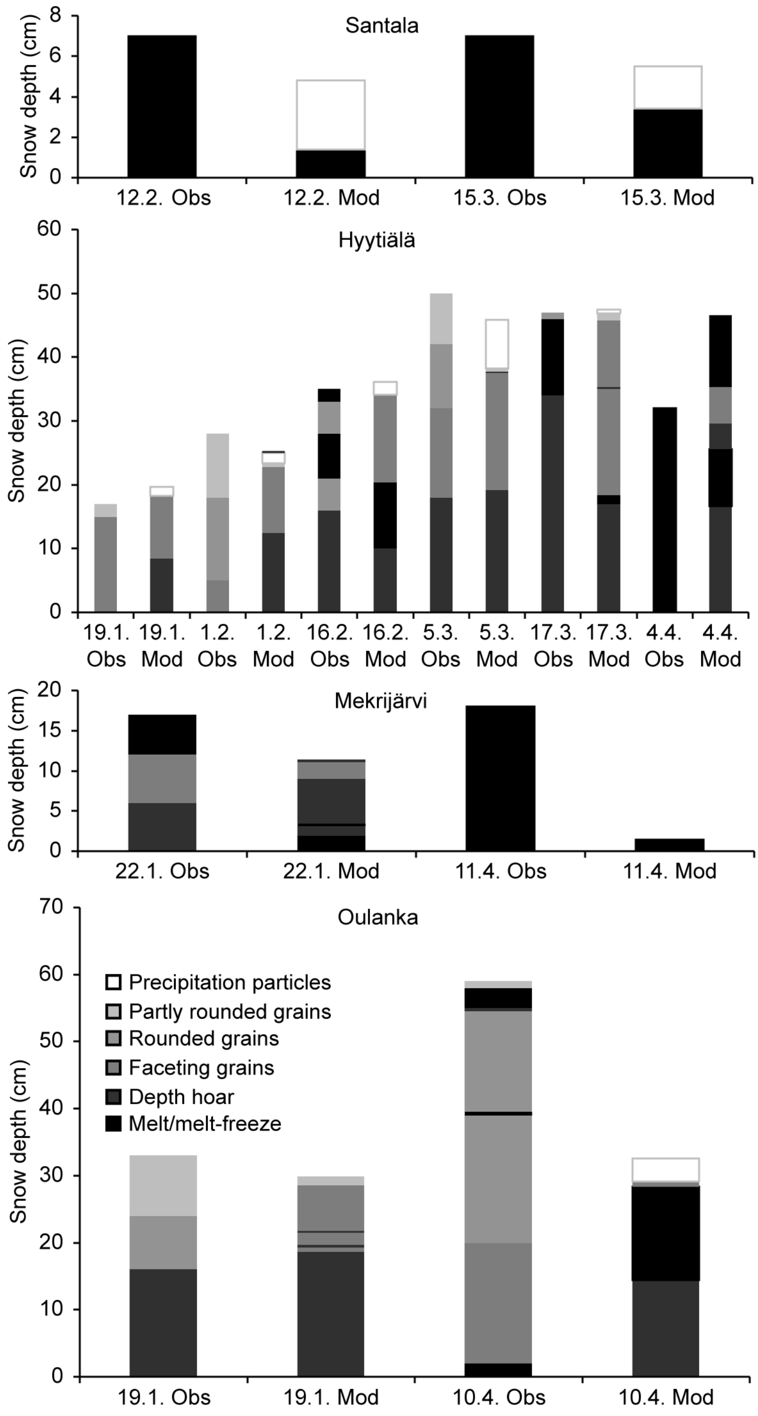

Fig. 10. The observed and modelled snow pack structure in Santala, Hyytiälä, Mekrijärvi and in Oulanka during early and late winter 2000/2001. FMI precipitation data used in SNOWPACK –model calculations instead of snow depth information.

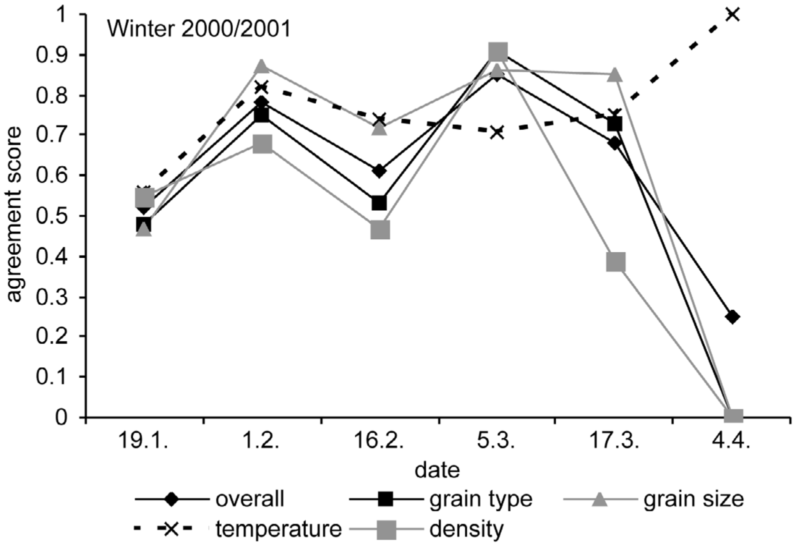

Fig. 11. The evolution of the agreement scores during the winter 2000/2001 in Hyytiälä.

were made, but also an objective comparison method was used. This means the calculation of agreement score (*see* also Lehning *et al*. 2001) between simulations and observations of each studied snowpack structure quantity, and overall agreement score. In this method, the modeled snow profile is first stretched to match the height of the observed snow profile, and after this the mapping of the layers is performed to find the matching layers. Scores describing agreement between observed and modeled layer properties are calculated for each property separately, and finally these scores are combined as an overall agreement score using certain weighing factors for each property. Agreement score ranges between 0 (no agreement) and 1 (perfect agreement). Properties studied are temperature, density, liquid water content, grain size and grain type.

For the purposes of this study minor changes to the procedure described in Lehning *et al*. (2001) were made. Liquid water content was not taken into account in calculations, because of the lack of field measurements. Weighing factors for all of the studied properties were kept as 1, and so all of the properties were treated as equally important.

When looking at the evolution of the agreement scores during the winter 2000/2001 in Hyytiälä (Fig. 11) it is seen that overall agreement between observations and simulations is quite high through the winter. The agreement score drops when melting starts, although the agreement score for temperature reaches 1 when the snow cover is isothermal. Scores for temperature and grain size are high through the winter, whereas grain type and density go through more changes.

No dramatic drop for the agreement score is seen during the melt period 2003 (Fig. 12). Here the score for grain type shows great variability, and also the score for the temperature is much more variable. For both winters the average overall agreement score was around 0.6, which is a reasonably good agreement between the simulations and observations.

The agreement scores for all of the locations except Hyytiälä are listed in Table 6. The scores could be calculated only twice a winter because of the lack of snow-pit observations. The snow profiles shown in Figs. 5–9 are used as observed snow profiles here.

The same trends like in Hyytiälä's case can be found here: the scores are relatively high especially in the early winter cases and with the exception of ephemeral Santala; temperature and grain size have normally higher scores than grain type and density.

The conditions during the especially good (overall agreement score more than 0.80) and poor agreement (overall agreement score smaller than 0.30) were studied. Also the Hyytiälä scores

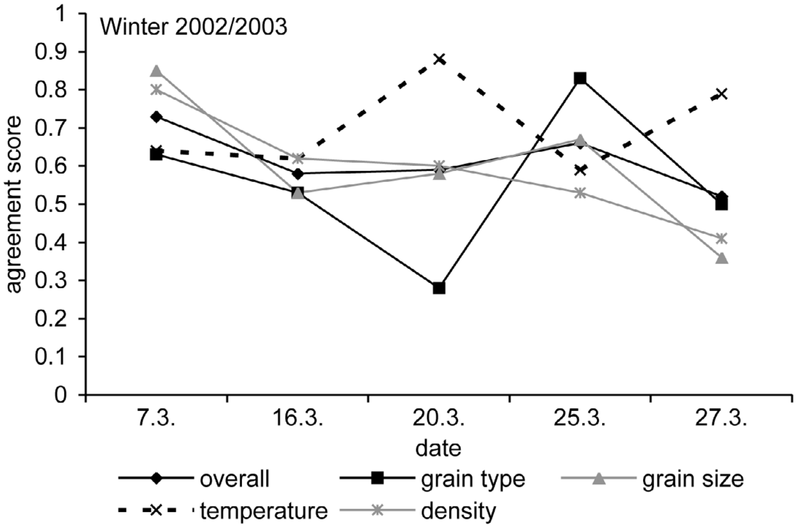

Fig. 12. The evolution of the agreement scores during the melt period 2003 in Hyytiälä.

were taken into account. Some common features were found from the snow conditions and weather conditions during the good agreement scores: the snow depth was quite homogenous in the area, the snow was relatively soft and porous and consisted of "winter snow", meaning in most of the cases dry rounded and faceted snow in turns. The weather was cold and dry. Also during poor agreement scores some common features could be found: in most of the cases the snow was isothermal, dense, hard and wet or melting. The snow depth was not homogenous; maybe

Table 6. The agreement scores for different locations during early and late winters 1999/2000 and 2000/2001.

	Overall	Grain type	Grain size	Temperature	Density
1999/2000					
Santala					
Early winter	0.25	0	0	1	0
Late winter	0.48	0.13	0.80	1	0
Mekrijärvi					
Early winter	0.67	0.70	0.77	0.69	0.50
Late winter	0.60	0.67	0.58	0.67	0.49
Oulanka					
Early winter	0.65	0.78	0.54	0.63	0.63
Late winter	0.76	0.57	0.83	1	0.64
Kilpisjärvi					
Early winter	0.65	0.43	0.89	0.67	0.61
Late winter	0.88	0.92	0.82	0.86	0.93
2000/2001					
Santala					
Early winter	0.54	0.50	0.50	0.52	0.65
Late winter	0	0	0	0	0
Mekrijärvi					
Early winter	0.76	0.67	0.78	0.58	0.82
Late winter	0.28	0.05	0.35	0.63	0.07
Oulanka					
Early winter	0.88	0.85	0.89	0.90	0.88
Late winter	0.51	0.37	0.50	1	0.17
Kilpisjärvi					
Early winter	0.77	0.77	0.68	0.81	0.83
Late winter	0.81	0.81	0.91	0.68	0.86

there were bare plots on the ground already. The weather was warm. Also the quality of the measurements naturally affects the agreement scores: replacing the measured grain sizes and densities with estimates, differing grain type definitions and snow pit depth deviating from the local average all worsened the agreement scores slightly. The varying scores for grain type and density can also mean that the observers did not report consistent grain types from one visit to the next.

Model sensitivity

Test and sensitivity simulations

To test the sensitivity of the model output to changes in model input or boundary conditions several test runs were made. Sensitivity tests aimed at two goals: to see which output quantities are most sensitive to the changes in input, and on the other hand to see which input quantities have the greatest effect on the modelled snow pack structure.

Sensitivity testing was done using SMEAR II data from Hyytiälä Forest station (Table 7). The control run, which was used as a baseline to which all the other run outputs were compared, consists of measured air temperature, relative humidity, wind speed, wind direction and incoming solar radiation with 30 min time resolution. In addition the snow depth observations from FMI were used. Snow surface temperature was set to air temperature and ground surface temperature to 0 °C. Cloudiness observations from FMI were used when incoming short wave and long wave radia-

Table 7. The runs made in the sensitivity testing of the SNOWPACK model and the changes in input in these runs compared to the control run.

Run	Differences
Control	–
Dirilecht	Run made with Dirilecht, not with Neumann boundary conditions
Iqbal	Short wave radiation calculated using Iqbal parameterisation
Longwave	Long wave radiation calculated using parameterisation by Omstedt
Precipitation	Snow depth replaced with precipitation data
FMIsnow	6h synoptic data, Iqbal parameterisation in shortwave radiation, snow depth
FMIprecipitation	6h synoptic data, Iqbal parameterisation in short wave radiation, precipitation
Water	Residual water content set to 0.04 (original 0.05)
ConstantAlbedo	Albedo model output replaced by constant albedo 0.78
Alb_old	Old albedo model (SLF1) used
Albmodel3	Most recent albedo model (SLF3) used
New_alb	New snow albedo set to 0.78 (original 0.90)
New_grsz	New snow grain radius set to 0.2 mm (original 0.15)
Dens_old	Old model for new snow density used
Density	New snow density model output replaced by constant density 100
AddTair	20% added to air temperature
AddRH	20% added to relative humidity
AddWS	20% added to wind speed
AddRad	20% added to short wave radiation
AddTsnow	20% added to surface temperature
AddTGround	20% added to bottom temperature
AddDepth	20% added to snow depth
DimTair	20% reduction to air temperature
DimRH	20% reduction to relative humidity
DimWS	20% reduction to wind speed
DimRad	20% reduction to short wave radiation
DimTsnow	20% reduction to surface temperature
DimTGround	20% reduction to bottom temperature
DimDepth	20% reduction to snow depth
AddTsnowDIR	20% added to surface temperature, Dirilecht boundary conditions
DimTsnowDIR	20% reduction to surface temperature, Dirilecht boundary conditions
3h	Control run time resolution changed to 3 hours
6h	Control run time resolution changed to 6 hours

tions were calculated; precipitation data comes also from FMI. Neumann boundary conditions have been used in the control run simulation.

After each run the following quantities were studied from the model output:

- date of snow cover formation,
- date of snow melt,
- date of maximum snow depth,
- date of first complete wetting of the snow pack,
- maximum snow depth,
- maximum snow water equivalent.

In addition, from the modelled snow profiles for 15 March (the average date for present day maximum snow depth), the following quantities were calculated:

- snow depth,
- snow water equivalent,
- bulk density,
- bulk temperature,
- bulk grain size,
- fraction of new or rounded grain snow,
- fraction of faceted grain or depth hoar snow,
- fraction of icy or melting snow.

The most sensitive snow parameters

The absolute changes in percentages for all of the studied quantities were calculated between each test run and control run. For quantities including dates the percentile differences were calculated by comparing differences in dates to snow cover duration; temperature was handled in degrees of centigrade; quantities which already are fractions calculated in percentages, simple subtraction of the control and sensitivity run outputs was carried out. The changes for different quantities were after this arranged by different runs. The quantities most often seen in the top 5 of the sorted tables were looked for, because these were the quantities most sensitive to the changes in input or boundary conditions of the runs (Table 8). Thirteen different quantities could be found in top 5 ranges of the 31 runs, so for most of the runs the same quantities are the most sensitive ones.

Table 8. The most sensitive snow cover quantities in SNOWPACK model based on the sensitivity test.

Quantity	Times in top 5
WE	35
Bulk temperature 15 Mar.	19
Grain form 15 Mar.	19
Bulk grain size 15 Mar.	16
Depth	15
Melt	12
Bulk density 15 Mar.	7
Duration	6
Wetting	6

In class “grain form” the changes in fractions of faceted snow, rounded grain snow and wet or icy snow are combined; in class “WE” the same has been done to maximum water equivalent of the snow cover and water equivalent on 15 March; and in the class “Depth” for maximum snow depth and depth on 15 March.

The amount of snow seems to be most sensitive (combining WE and depth), after this the snow pack structural characteristics (bulk temperature, grain form and size, density), and after this the snow cover evolution characteristics (melt, duration, wetting).

Some runs could be found, which had small or zero effect on all of the studied quantities. These were runs with added ground temperature, altered new snow albedo, constant albedo and altered residual water content. For most of the cases the changes were large (more than 10%) for only a few of the quantities. For runs with precipitation used as input, the changes were larger than for other runs.

In many cases input data for the modelling has poor time resolution (6 h), the incoming solar radiation has to be estimated (for example Iqbal - parameterization) and snow depth data have to be replaced with precipitation data. The maximum changes, or errors, found in these analyses were 8%, 21% and 41%, respectively, for the most sensitive quantities (snow temperature, grain size and amount of snow). Changes for other quantities ranged between 0%–4% for runs with 6-h time resolution and estimated solar radiation, compared to the control run cases, and between 3%–28% for precipitation used as input.

The runs with largest effects

The other possible way to study the model sensitivity is to turn around the sorting method described above. Now the changes caused by different runs were arranged by different snow quantities studied. The runs most often seen in the top 5 of the sorted tables were looked for, because these were the runs having the greatest effects on changes in modelled snow conditions (Table 9). 15 different runs could be found in the top 5 ranges of the 15 quantities, so the scattering here is larger than for the most sensitive quantities case. Like in the section above, the bottom 5 values were not analysed because zero or very small effects were common.

Most of the runs with large effects can be classified either as runs having changed amount of snow (39 times in top 5) or as runs having changed radiation scheme (24 times in to 5). Runs with changes in relative humidity, time resolution or new snow parameterization had minor effects.

The precipitation/snow depth runs were most important for snow cover formation, depth and water equivalent and changes in radiation for snow melt and snow cover duration. For other quantities the effects were not so easily classified. Runs with changed snow surface temperature were made using the Dirichlet boundary conditions also; these runs appeared to have an effect on grain size on 15 March as well as for snow bulk density and water equivalent on 15 March. For most of the quantities, not all of the runs had any effect; in many cases only one or two thirds of the runs affected the model outputs.

Discussion on the reliability and the use of the SNOWPACK model in Finland

SNOWPACK simulates snow depth and snow pack structure evolution satisfactorily in Finnish conditions. Only in the ephemeral snow zone the model has serious difficulties.

In the spring time the modelled snow depth is typically overestimated by the SNOWPACK model, and the melting is too slow. There are several possible reasons for this model behaviour. One is that the snow settling in the model is too fast, and therefore too much mass accumulates in the modelled snow cover when using the snow depth as input. Too high modelled water equivalent values compared to the observed ones support this theory, but on the other hand the ablation periods during the winter show the modelled snow settling following the observed one closely.

The Iqbal parameterisation for incoming short wave radiation may be underestimating the radiation, or the albedo scheme of the SNOWPACK model is not good for the melting period in Finland. The latter may have significance: some runs were made using the most recent albedo model in the SNOWPACK, which seems to be more suitable for melting snow albedo calculations. In these simulations slight improvement of melting season snow depth was seen, but it did not totally solve the problem. The measured and Iqbal parameterised short wave radiation fluxes in Hyytiälä in winter 2000/2001 melting period were studied closely. The overall agreement between these two is excellent, and it is shown also in some statistics of the two radiation data sets: measured radiation ranged between 0 and 743 W m^{-2}, and calculated between 0 and 655 W m^{-2}. Averages and standard deviations were 116 and 160 W m^{-2} for measured and 127 and

Table 9. The sensitivity test runs with largest effect on SNOWPACK model outputs.

Run	Times in top 5
Precipitation	12
FMIprecipitation	11
Dirilecht	7
Iqbal	6
FMIsnow	6
DimDepth	6
Alb_old	5
AddDepth	4
6h	3
Longwave	3
DimRad	2
Constant_albedo	2
AddRh	2
Density	1
New_grsz	1

151 W m^{-2} for calculated values, respectively. The other possible reason for the difference between these data sets is cut-off of the maximum radiation periods in the calculated case, which can of course be important for the snow pack energy balance.

Another possibility is the error in energy input, because liquid precipitation could not be taken into account when the snow depth was used as input for the model. Large amounts of heat is transported to the snow cover by rain during the melt period. When comparing the melting in the model runs using snow depth as input and in the model runs using precipitation as input it is seen that melting is more rapid and more realistic in the precipitation cases. On the other hand quite severe problems are seen in the middle winter snow depth in Santala and in Oulanka, when using precipitation as input. This might be due to some combined effect of weather during the measurement winters and model behaviour. Not necessarily enough of the observed precipitation has been used by the model to increase the snow depth, because of large fraction of the liquid precipitation, and perhaps the real snow precipitation exceeds greatly the observed one. The correction of the precipitation should be done knowing all the details on wind patterns, liquid/solid partition of the precipitation and the situation of the precipitation gauge.

In the testing, a model version comparable to the Operational version 5.0 has been used. In the more recent model versions some of the problems stated above are solved, especially the water transport and melting are treated more efficiently (Etchevers *et al.* 2005).

Grain type agreement scores were calculated by Grönholm (2003) for all of the locations for winter 2000/2001. The values ranged between 0.7 and 0.95 in Hyytiälä, 0.3 and 0.7 in Santala, 0.3 and 0.8 in Mekrijärvi, 0.9 and 0.93 in Oulanka and between 0.78 and 0.92 in Kilpisjärvi. These results were somewhat higher than the results of this study. Small changes may be due to different classification for grain types and layering typical for any two measurers. Please note that agreement score should not be confused with the correlation coefficient R^2. The usable values of agreement score range between 0 and 1, and also small values give knowledge about agreement or disagreement between two profiles. Values around 0.6 and 0.7 show very reasonable agreement between two profiles.

The results of this study are in good agreement with the earlier ones. Comparisons between simulated and measured snow profiles in the Swiss Alps have shown good general agreement. The overall agreement score of 0.8 all through the winter was found in the study by Lehning *et al.* (2001). The score was highest for the temperature, whereas grain type and grain size reach lower scores. A small systematic overestimation of modelled water equivalents have been noted, as well as a systematic underestimation of the melt rate during the final stage of the melt season. (Bartelt *et al.* 2002)

Use of the air temperature as snow surface temperature may cause errors in SNOWPACK simulations, but based on the sensitivity tests the effect of the error seems to be small. The same can be said of the 0 °C ground temperature assumption. Naturally it would be ideal to have observations also of these quantities as input. Time resolution of 3 or even 6 hours did not affect very much the model output.

In most of the conditions in Finland, the use of snow depth instead of precipitation is recommended. Attention should be paid to the accuracy of the snow depth and radiation input, as these seem to have the largest effects on the model output. This is especially true during the melt period. It is recommended to use higher value than 0.05 to residual water content

Even if the SNOWPACK model works reasonably well in Finnish conditions, modifications should be made before it could be taken in extensive use in Finland. Wet snow metamorphism and water transport routines should be checked, together with albedo and new snow parameterisation using Finnish observations. User often has only synoptic meteorological observations as input data to the model. It would be good to take this into account also in model development. Interface program estimating snow surface temperature, ground surface temperature as well as incoming long wave and short wave radiation should be possible to develop using long time series of observations on these and synoptic meteorological observations on for example air temperature, wind speed and cloudiness. Measured precipitation could also be corrected by this program using knowledge of local conditions.

Adding of forest layer between the atmosphere and snow cover is very important for use of SNOWPACK model in a forested country like Finland. It is clear that the parameterization of the initial and boundary condition equations should be validated and modified when starting the model use in forested conditions. Wind speed, affecting the sensible and latent heat fluxes has to be estimated and transfer coefficients of the fluxes changed, long wave emissivity of the canopy has to be taken into account as well as snow interception and short wave radiation extinction in the canopy. The snow surface temperatures are normally higher in the forest than in the open area, so the difference between air and surface temperature is decreased in the forest. Changes in air temperature and wind speed have an effect on new snow density; albedo may be affected by the litter on the surface. Falling snow may have different properties in forested areas as compared with snow falling in open areas. Therefore, when studying snowcover properties the fractions of forest and open areas in a study location should be known.

Conclusions

In this work validation of the Swiss SNOWPACK model in Finnish conditions has been described, as well as sensitivity testing of the model.

Measured and simulated snow depth agreed very well during the accumulation periods observed during this study, as well as during the dry snow settling and blowing snow periods. During the melt the snow depth was overestimated, and snow melt was prolonged by an average of 7%. Modelled snow water equivalent was most often overestimated. This might be due to too high a snow pack settling rates and because of this to too high a density.

Visual agreement between the snow pack structure observations and simulations was reasonably good throughout the country. There were problems with modelling of snow depth when using precipitation as input; on the other hand the melt period and snow pack structure were better simulated in some cases. Agreement scores between the observed and simulated snow profiles were highest for temperature and grain size, and lower for grain type and density. Agreement scores were generally high during the early and middle winter and dropped during the melting period. Agreement scores reached higher values when going towards the north and towards more stable snow zones in Finland. In the ephemeral zone scores were low and very variable.

The most sensitive snow parameters in this study were snow water equivalent, temperature, grain form and size, snow depth and timing of the snow melt. The runs using precipitation instead of snow depth, different boundary conditions, different short wave radiation scheme and slightly changed snow depth had the largest effects on the model outputs. The model sensitivity grew towards the melting period, and also the choices of the input data and boundary conditions became more important during that time.

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References

Bartelt P. & Lehning M. 2002. A physical SNOWPACK model for the Swiss avalanche warning: Part I. Numerical model. *Cold Reg. Sci. Technol.* 35: 123–145.

Brun E., David P., Sudal M. & Brunot G. 1992. A numerical model to simulate snow-cover stratigraphy for operational avalanche forecasting. *Journal of Glaciology* 38: 13–22.

Etchevers P., Martin E., Brown R., Fierz C., Lejeune Y., Bazile E., Boone A., Dai Y.J., Essery R., Fernandez A., Gusev Y., Jordan R., Koren V., Kowalczyk E., Nasonova N.O., Pyles R.D., Schlosser A., Shmakin A.B., Smirnova T.G., Strasser U., Verseghy D., Yamazaki T. & Yang Z.L. 2005. Validation of the energy budget of an alpine snowpack simulated by several snow models (SNOWMIP project). *Annals of Glaciology* 38: 150–158.

Eurola S., Kyllönen, H. & Laine K. 1980. Lumen ekologisesta merkityksestä kasvillisuudelle Kilpisjärven alueella. *Luonnon Tutkija* 84: 43–48.

Grönholm T. 2003. *Lumipeitteen rakenteen SNOWPACK mallin toimivuus Suomen lumivyöhykkeillä*. M.Sc. thesis, University of Helsinki.

Iqbal M. 1983. *An introduction to solar radiation*. Academic Press, Canada.

Jordan R. 1991. *A one-dimensional temperature model for a snow cover*. CRREL Special Report 91-16.

Koivusalo H., Heikinheimo M. & Karvonen T. 2001. Test of a simple two-layer parameterisation to simulate the energy balance and temperature of a snow pack. *Theor. Appl. Climatol.* 70: 65–79.

Kuusisto E. 1973. Lumen sulamisesta ja sulamiskauden vesitaseesta Lammin Pääjärvellä 1970–72. *Vesihallituksen tiedotus* 46: 1–104.

Laevastu T. 1960. Factors affecting the temperature of the surface layer of the sea. *Commentat. Phys. Math.* 25: 1–136.

Lehning M., Fierz C. & Lundy C. 2001. An objective snow profile comparison method and its application to SNOWPACK. *Cold Regions Science and Technology* 33: 253–261.

Lehning M., Bartelt P., Brown B., Fierz C. & Satyawali P. 2002a. A physical SNOWPACK model for the Swiss avalanche warning. Part II. Snow microstructure. *Cold Reg. Sci. Technol.* 35: 147–167.

Lehning M., Bartelt P., Brown B. & Fierz C. 2002b. A physical SNOWPACK model for the Swiss avalanche warning service. Part III. Meteorological forcing, thin layer formation and evaluation. *Cold Reg. Sci. Technol.* 35: 169–184.

Lundy C., Brown R.L., Adams E.E., Birkeland K.W. & Lehning M. 2001. A statistical validation of the SNOWPACK model in a Montana climate. *Cold Reg. Sci. Technol.* 33: 237–246.

Niemelä S., Räisänen P. & Savijärvi H. 2001. Comparison of surface radiative flux parameterizations. Part II. Shortwave radiation. *Atmospheric Research* 58: 141–154.

Omstedt A. 1990. A coupled one-dimensional sea ice-ocean model applied to a semi-enclosed basin. *Tellus* 42A: 568–582.

Pomeroy J. & Brun E. 2001. Physical properties of snow. In: Jones H., Pomeroy J., Walker D. & Hoham R. (eds.), *Snow ecology*, Cambridge University Press, USA, pp. 45–126.

Solantie R. & Junila P. 1995. *Sademäärien korjaaminen Tretjakovin ja Wildin sademittarien vertailumittausten avulla*. Meteorologisia julkaisuja 33, Finnish Meteorological Institute, Helsinki.

Sturm M., Holmgren J. & Liston G.E. 1995. A seasonal snow cover classification scheme for local to global applications. *J. Climate* 8: 1261–1283.

Venäläinen A. 1994. *The spatial variation of mean monthly global radiation in Finland*. M.Sc. thesis, University of Helsinki.

Vesala T., Haataja J., Aalto P., Altimir N., Buzorius G., Garam E., Hämeri K., Ilvesniemi H., Jokinen V., Keronen P., Lahti T., Markkanen T., Mäkelä J.M., Nikinmaa E., Palmroth S., Palva L., Pohja T., Pumpanen J., Rannik Ü., Siivola E., Ylitalo H., Hari P. & Kulmala M. 1998. Long-term field measurements of atmosphere-surface interactions in boreal forest ecology, micrometeorology, aerosol physics and atmospheric chemistry. *Trends in Heat, Mass and Momentum Transfer* 4: 17–35.